Hadron Production Ratios as Probes of Confinement and Freeze-Out

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Particle production in central S-A collisions at 200 GeV/A energy is analysed within a thermal model. Present data imply that the strange particles freeze out at a higher temperature than the non-strange particles and that the strangeness saturation is incomplete.

Introduction: A significant enhancement of strange particle production has been observed in high energy heavy ion collisions in comparison to proton- proton collisions. This indicates a higher level of equilibration in nuclear collisions where volume, life-time and energy density are increased. Strongly interacting matter produced initially expands rapidly, cools down and breaks up into observable hadrons. It is not excluded that a quark-gluon plasma phase in which the colour degrees of freedom are deconfined is achieved at an early stage of evolution. Soft processes involved in the transition from quarks and gluons to hadrons are, if at all, only poorly understood. It is possible that the system expands too fast to retain equilibrium and a quark-gluon plasma suddenly disintegrates into the final hadrons. In this case the observed hadrons could carry information on parameters and properties of quark- gluon plasma and on confinement [1, 2]. We assume here a smooth evolution in which a hadron gas thermalises before the final hadrons stop interacting. Regardless of the exact nature of the produced matter, the observed hadrons will reflect the properties of the last thermal state before the freeze-out, the equilibrium hadron gas. In the present paper we shall study data on hadron production ratios within the framework of a thermal model to determine the statistical properties of their sources, i.e. of particle freeze-out states.

Thermal Model: The state of an equilibrium hadron gas is specified by three parameters, the temperature T, the baryon chemical potential μ_B and the strangeness chemical potential μ_s. The requirement of vanishing overall strangeness fixes one of these parameters, e.g. μ_s, and the two remaining parameters, T and μ_B, fully determine the local state in the thermal model. For simplicity, we present the formulae in Boltzmann statistics although in the actual calculations we have worked with the quantum statistics. The partition function of the hadron gas is given by [1]

$$\ln Z(T,\mu_B,\mu_s) = \sum_i \left[W_i^m + \left(\lambda_B^{B_i} \lambda_S^{-S_i} + \lambda_B^{-B_i} \lambda_S^{S_i} \right) W_i \right]. \tag{1}$$

Here the first term refers to non-strange mesons and the second term to particles which carry baryon numbers B_i and strangeness S_i. The fugacities related to the baryon number and strangeness are $\lambda_B \equiv \exp(\mu_B/T)$ and $\lambda_S \equiv \exp(\mu_s/T)$. The phase space factor W_i is of the form

$$W_i = \frac{d_i V T m_i^2}{2\pi^2}\, K_2\left(\frac{m_i}{T}\right) \tag{2}$$

where d_i denotes the degeneracy and m_i the mass of the hadron state i, V is the volume of the system and K_2 the modified Bessel function of the second type. We have included in eq.(1) all well established resonances up to mass of 2 GeV. The thermal contribution of the particle multiplicity $N_i^{th} = W_i$ calculated from eq.(1) has to be added by the resonance contributions to get the particle multiplicity,

$$N_i = W_i + \sum_j \Gamma_{ij}\, W_j. \tag{3}$$

Here Γ_{ij} is the branching ratio of the decay of resonance j to particle i. If both thermal and chemical equilibrium

were established and if there were a unique freeze-out for different hadron species, then all hadron production ratios would be determined using the values of T and μ_B fixed by two measured ratios.

Data Interpretation: Data we consider here are from sulphur collisions at 200A GeV energy with tungsten- [3, 4], silver- [5] and lead- [2, 6, 7] targets. They are measured in the backward hemisphere, 2.3 < y < 3.0, where the production ratios do not depend much on the target size. The WA85 experiment [3, 4] provides us with the following strange baryon and antibaryon ratios: $\bar{\Lambda}/\Lambda = 0.2 \pm 0.01$, $\overline{\Xi^-}/\Xi^- = 0.45 \pm 0.05$, $\Xi^-/\Lambda = 0.095 \pm 0.006$, $\overline{\Xi^-}/\bar{\Lambda} = 0.21 \pm 0.02$ and $\overline{\Omega^-}/\Omega^- = 0.57 \pm 0.41$. The ratios for Ξ^-/Λ and $\overline{\Xi^-}/\bar{\Lambda}$ have been corrected for the p_T cut while the result for $\overline{\Omega^-}/\Omega^-$ is preliminary and uncorrected for the acceptance. The first two ratios lead to the narrow bands in the $T - \mu_B$ plane which cross each other in the small region of $T \simeq (190 \pm 15)$ MeV and $\mu_B \simeq (240 \pm 40)$ MeV, as shown in Figure 1. The crossing region corresponding to the ratios for Ξ^-/Λ and $\overline{\Xi^-}/\bar{\Lambda}$ is quite different, as also shown in Figure 1. The thermal model in its original form thus turns out to be too idealized to explain WA85 data. A remedy we use is to leave out the assumption from the complete chemical equilibrium between strange and non-strange hadrons. In fact it has been suggested, on the basis of small cross-sections of strange particle production, that the strange particle phase space can reach only partial saturation [2, 8, 9]. The exchange processes among the strange particle species are faster than strangeness producing processes and therefore the strange particles are assumed to be in equilibrium relative to each other but in relation to the non-strange particles they may be suppressed by a phase space saturation factor $\gamma_s < 1$ [8]. This is achieved in our model by multiplying both λ_S and λ_S^{-1} in eq.(1) by a parameter γ_S which then yields for the multiplicity of particle species i,

$$N_i = \gamma_S^{S_i} W_i + \sum_j \gamma_S^{S_j} \, \Gamma_{ij} \, W_j. \tag{4}$$

The ratios for $\bar{\Lambda}/\Lambda$ and $\overline{\Xi^-}/\Xi^-$ are not changed by the modification while the results for Ξ^-/Λ and $\overline{\Xi^-}$ become multiplied by factor γ_S. As shown in the figure, the thermal model with $\gamma_S = 0.7$ is compatible with the WA85 measurements on Λ, $\bar{\Lambda}$, Ξ^- and $\overline{\Xi^-}$ production. We notice, however, that the three independent data points have been used to fix three statistical parameters T, μ_B and γ only. More data is needed to justify the validity of the model. The model prediction for $\overline{\Omega^-}/\Omega^-$ (1 ± 0.3) is higher than the preliminary experimental ratio. On the other hand, the results for K_s^0/Λ and K^+/K^-, $K_s^0/\Lambda \cong 1.2 \pm 0.5$ (2.3 < y < 2.8) and $K^+/K^- \simeq 1.5 \pm 0.5$ (y $\simeq$ 2.3) obtained from NA35 measurements on rapidity distributions in S-Ag collisions [5] are well predicted by the model with the above values of T and μ_B. Having extracted the freeze-out parameters for strange particles to be $T \simeq 190$ MeV, $\mu_B \simeq 240$ MeV and $\gamma_S \simeq 0.7$ we turn our attention to the non-strange hadron production. The non-strange particles dominate the charged particle multiplicities which have been measured by EMU05 [2] and NA35

[5] collaborations. From EMU05 we have a result for the charge asymmetry ratio, $D_Q = (h^+ - h^-)/(h^+ + h^-)$ $= 0.088 \pm 0.007$, measured in S-P collisions using the same rapidity window as for WA85 results. The ratio D_Q is closely related to the entropy per baryon (S/B), D_Q(S/B) $\simeq 4.5$, from which one obtains S/B $\simeq 50$ [2]. In order to see whether this value is consistent with the thermal model we show in Fig.3 the entropy per baryon in the hadron gas for several different temperatures. It is seen that at T and μ_B required by strange particle ratios, S/B $\simeq 30$, which is lower than the measured value 50. The measured value would correspond to temperature 110 MeV $< T <$ 140 MeV as seen in Fig.3. Almost the same temperature and chemical potential, 120 MeV $< T <$ 140 MeV and 200 MeV $< \mu_B <$ 270 MeV, can also be extracted from NA35 measurements on $h^-/(p - \bar{p})$ in S-Ag collisions at $2.3 < y < 2.8$ [5]. Our interpretation for these results is that there is no unique freeze-out for strange and non-strange particles. The sequential freeze-out has immediate other experimental consequences. It implies a different freeze-out radius for kaons R_K than for pions R_π. The interferometry studies of NA44 on S-Pb collisions indeed measure $R_K < R_\pi$ [6, 7]. From free mean path arguments [1], assuming $\pi\pi$-cross- section to be twice as big as πK-cross-section, one gets $R_K/R_\pi \simeq 0.7$ which is rather well in agreement with NA44 results [6, 7]. For an isentropic expansion the freeze-out radius is inversely proportional to the freeze-out temperature; hence $T_K \simeq$ 190 MeV would imply $T_\pi \simeq 130$ MeV. This is consistent with the results of our analysis.

Conclusions: The production rates of different hadrons provide tools for the study of hadronisation and freeze-out stages in high energy heavy ion collisions. The measured ratios of strange and non-strange hadrons allowed us to determine the freeze-out parameters. Analysing data of several CERN collaborations (WA85, NA35, EMU05 and NA44) within a thermal model indicated that the strange particles freeze-out at higher temperature ($T \cong 190$ MeV) and at the same chemical potential ($\mu_B \simeq 240$ MeV) than the non-strange particles ($T \simeq 130$ MeV). The sequential freeze-out is consistent with the difference in the mean free paths of kaons and pions in the medium. The saturation of the strangeness was found to be incomplete.

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